An Investigation into the Effect of the Temperature of a Medium on the Speed of Sound

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Abstract

This essay is an examination of how the speed of sound was affected by the temperature of the medium it traveled through. An experiment was carried out to collect data which would allow me to reach a conclusion about the relationship between the two variables. A device was constructed which would allow for the data to be collected. In tandem with the device, a computer program was used to extract quantitative values from the experiment. From the data collected, the relationship between temperature and speed could be determined. What I found was that there is a direct positive correlation between the two variables (see appendix for table and graphs). In order to know the accuracy of the experimental values, I carried out several calculations to find theoretical values. Next, comparing the theoretical values to the experimental ones, I found the accuracy of the experiment. I then offered possible explanations as to the reason behind the relationship. Finally, sources of error were evaluated and ways to improve the experiment were stated.

HOW IS THE SPEED OF SOUND AFFECTED BY THE TEMPERATURE OF ITS MEDIUM?

Introduction

The broader topic of physics was chosen due to my fascination and interest in the field. In order to further my knowledge in physics, it was only natural for me to pick a specific topic from within physics. The speed of light has been an area of extreme curiosity for me; however, because of the numerous limitations when dealing with the subject, I chose a similar aspect of physics, the speed of sound. To narrow the focus of my topic to manageable proportions, I decided to specifically study how the speed of sound changes in different temperatures of water.

The implications of varying speeds of sound can be immense. The primary situation in which this is important is in Sound Navigation and Ranging (SONAR) aboard submarines and other aquatic vessels. SONAR works emitting a sound to determine where objects are located. The sound wave will travel straight until it comes in contact with a foreign object, for example, another submarine, at which point it is reflected off of the object's surface. From the reflected sound wave, the location of the foreign object can be calculated. Therefore, since the whole system is dependent on the speed of sound to determine the distance of the foreign object, it is vital to account for the fact that the speed of sound will change based on the temperature of the water. Not doing so could give an incorrect position of an object and if the submarine were to fire a torpedo at it, it may miss because of the miscalculated distance.

Similarly, the speed of sound in the air can be important in the field of meteorology. Since both liquid water and air will behave in the same way due to fluid dynamics, the relationship between temperature and speed will be the same. In the primitive way of calculating the distance of a thunderstorm by counting the number of seconds between a flash of lightning and thunder, it is necessary to know the temperature of the air through which the sound wave must travel. Two extremes such as Hawaii and Alaska can experience temperature differences in excess of 30 °C. These drastically different temperatures can result in a miscalculation of more than 15 m/s (approximately 30 mph). Such a bad miscalculation can result in improper warnings for severe weather in a particular area.

One may be quick to dismiss the importance of knowing the exact speed of sound and just use the "universal" value of 343 m/s in all cases. However, as can be seen in the above examples, the implications of the speed of sound can have drastic effects. Therefore, it is necessary to study the subject and implement the findings in order to have more accurate systems such as SONAR and weather forecasts.

The experiment demonstrates on a smaller scale how the speed of sound is affected by the temperature of the medium it travels through.

Experiment:

Independent Variable: Temperature of water

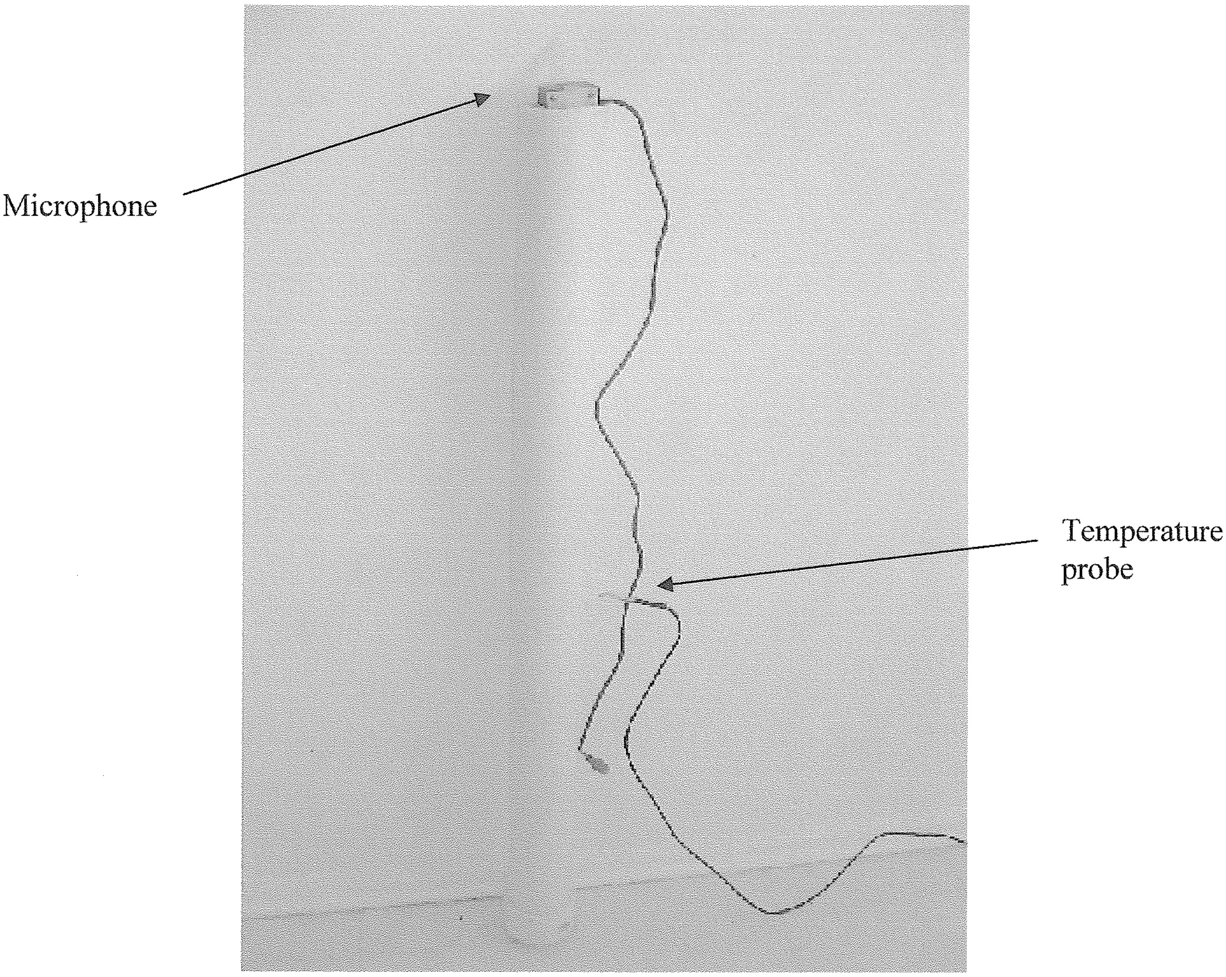
Dependent Variable: Speed of Sound (calculated by measuring time)

Method

In order to measure the fluctuation of the speed of sound, a device for holding the medium was constructed. A 1.1 meter long polyvinylchloride tube with a 7.5 cm diameter was used for this purpose. To measure the average temperature in the tube, a 0.6 cm diameter hole was drilled half way down the tube at a location of 55 cm from either end. A temperature probe was inserted into the hole so that the end of the probe was located directly in the center of the tube, both lengthwise and widthwise. Clay was used to secure the temperature probe in place and create a watertight seal between the tube and probe. Next, a polyvinylchloride cap was placed at one end of the tube and was sealed with silicone caulking for a watertight seal between the tube and cap. A meter stick was inserted into the open end of the tube so that one end rested against the inside of the cap. From this part of the procedure, a 1 meter mark was traced along the inside of the tube; this would indicate the point to which the water must be filled.

At this point, it was necessary to set up the Universal Lab Interface (ULI). The microphone was plugged into DIN 1 of the ULI and the temperature probe into DIN 2. To complete the set up, the sensors had to be selected and calibrated. This was done by opening the "Logger Pro" program and then clicking Setup>Sensors>"Sensor Setup" tab>DIN1. Next, "Microphone" was selected from the "Sensor" dropdown list. To set up the temperature probe, DIN2 was selected and "Temperature Direct Connect" was selected from the "Sensor" dropdown list. To receive accurate data, the temperature probe had to be calibrated and this was done by clicking the "Calibrate" tab of the "Sensor Setup" window and then clicking "Perform Now." It was unnecessary to calibrate the microphone because the correct sound level was irrelevant, only the time it took the sound to travel down the tube and reflect back up was needed. Therefore, the microphone was not calibrated. With the temperature probe sitting in room temperature, "22" was entered in the "Value 1" textbox. When the "Input 1" value steadied, the value was inputted by clicking "Keep." With the end of the temperature probe grasped in one hand, “36” was entered in the second “Value 1” text box and when the value steadied, the value was inputted by clicking “Keep.” After completing the set up of the sensors, the data collection options had to be specified. This was done by entering the “Data Collection” window through the Setup menu and inputting various values. On the first tab, “Mode,” “Real Time Collect” was selected from the dropdown list. On the “Sampling” tab, “16” was entered for experiment length and “milliseconds” was selected from the dropdown menu. In the “samples/second” text box, “11” was entered. On the “Triggering” tab, the “Enable Triggering” checkbox was checked and “3.5” was entered for the “Sound level is greater than” textbox (3.5 was used in this experiment because when the microphone was activated in the experimentation room, the value was approximately “2.5;” therefore, by using “3.5” as the trigger value, it would prevent an extraneous noise from being recorded and at the same time the microphone would only record the sound in the tube).

With the probes set up and the tube filled to the 1 meter mark, the data collection process could begin. The microphone was secured to the top of the tube so that it pointed towards the water and it sat just above the water’s surface. Next, the “Collect” button was clicked so the program would be able to start collecting data when the trigger value was exceeded. In order to trigger the data collection, a pencil was firmly hit against the outside of the tube at the 1 meter mark. At this point, a square-wave graph was displayed on the program. The time it took for the wave to travel down the tube and back up again was represented by the wavelength of the square-wave, the distance between one peak and the consecutive peak. In order to keep consistency, the middle of the peak was used each trial to calculate the time it took for the sound wave to be reflected back to the top.



Results:

Table 1: Times Gathered from Experiment (ms) ± .05

	Temperature (°C) ± 5			
	0	20	40	60
Average	1.10	0.97	0.94	0.86

The data collected from the experiment show that as temperature was increased, the time it takes for the sound to travel down the tube and back up again, decreased. This shows that there is a negative correlation between the two variables.

Analysis

To calculate the speed of sound, the average times were inputted into the formula, where d = 2:

$$v = d/t$$

which gives:

Table 2: Experimental Values for Speed of Sound	
Temperature (°C) ± 5	Speed (m/s)
0	1820.034
20	2060.071
40	2128.565
60	2327.746

The speeds can then be used to make a graph to see the correlation between temperature and the speed of sound (Appendix pg 1). These values are the experimental values and need to be compared to theoretical values to find out how accurate the experiment was.

In order to analyze the data results, one must first understand what sound is and how it travels – sound is a disturbance and it is propagated by the collisions of particles which produces a longitudinal wave. There are two valid arguments that can be made about the speed of sound regarding the temperature of its medium, however only one is true.

The first argument that can be made is that there is a direct, positive correlation between the speed of sound and the temperature of its medium. It is supported by the idea that since sound travels by the disturbance of particles, if the particles are moving faster, the wave will be able to move faster. According to kinetic theory, temperature is the average kinetic energy of particles of matter and because kinetic energy is defined as

$(1/2)mv^2$, temperature is directly related to velocity. Therefore, if the velocity of particles is increased by increasing the temperature, the sound wave is able to travel faster through the medium. This is because since the particles will already be moving relatively faster, it is easier for the sound wave to propagate through the medium.

The second argument is that there exists an indirect, negative correlation between the speed of sound and the temperature of its medium. This argument is also based on kinetic theory. However, it differs in that it focuses on the density rather than velocity. According to kinetic theory, as temperature increases, particles vibrate more and more and get farther and farther away. This ultimately states that temperature is directly related to density. From this, the argument is that if temperature is increased, and thus density decreased, the speed of sound will decrease because the particles, which must interact to propagate the wave, are farther apart. Therefore, since they are unable to interact as easily as when they were closer together in a lower temperature, the speed of sound will be slower.

On the broader scale of solids, liquids, and gases, the latter argument is correct. This is due to the fact that through experimentation one finds as temperature is increased (by changing the state of matter), the speed of sound decreases. The particles get so far apart in a gas that it is difficult for the wave to propagate through the medium.

To calculate the theoretical values for this experiment, the following equation must be used (Nave):

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}} = \sqrt{\frac{B}{\rho}} \quad \text{where}$$

B = bulk modulus

ρ = density

Upon referencing the bulk modulus of water, one finds that it is (2.2 * 10^9) N/m^2 (Nave), which gives:

$$v = \sqrt{\frac{2.2\times10^9\ \ N/m^2}{density}}$$

Note Density must be given in kg/m^3

The density of each temperature was found by using the online water density calculator. By inputting the temperatures of the water, it calculated the densities (Senese):

Table 3: Various Densities of Water

Temperature (°C) ± 5	Density (kg/m^3)
0	999.8425
20	998.2071
40	992.2187
60	983.2018

Using the densities above, one finds that the theoretical speeds are:

Table 4: Theoretical Values for Speed of Sound

Temperature (°C) ± 5	Speed (m/s)
0	1483.357
20	1484.571
40	1489.044
60	1495.857

To compare the experimental and theoretical values, percent error can be calculated using the formula:

% Error = (|theoretical – experimental|)/theoretical which gives the following values of percent error:

Table 5: Percent Errors for Experiment

Temperature (°C) ± 5	% Error
0	22.6970
20	38.7654
40	42.9484
60	55.6129

Conclusion

From the data collected in the experiment, one can conclude that there is in fact a direct positive correlation between temperature and the speed of sound. There are several possible sources of error in the experiment. First, the major source of error is most likely systematic error due to the fact that the experimental values were off of the theoretical values by approximately 550 m/s for each temperature. If it was human error, the experimental values would not have all been approximately the same amount off. The systematic error most likely lies in the microphone or Logger Pro software. What little human error there may have been may have been the force at which the pencil was struck since it was not exactly constant for every trial. This would alter the loudness of the wave and ultimately make it more or less difficult to calculate the time between two wave crests.

In order to conduct a more accurate experiment, there are several improvements which can be made. A more accurate and precise microphone which is specifically designed to measure very minute times should be used. This will ensure that the data gathered is closer to the theoretical value and thus reduce percent error. Secondly, a device for emitting an extremely short pulse of sound can be used so that it is easier to distinguish time between two consecutive wave crests. A cover for the top of the tube may also be used to keep the extraneous noise out of the tube and keep it from interfering with the data the microphone collects. These three changes will surely improve the data in future experiments and will therefore result in a better analysis.

There is, however, a question which remains unanswered at the conclusion of the experiment: why does the speed of sound increase with temperature, but decrease with state of matter? It is known that the speed of sound increases with temperature, as proven in the experiment, and that the speed of sound decreases with state of matter, as can be seen by referencing a table of the speed of sound in different mediums, but, the reason for this is unanswered. It is ironic that in one case the speed of sound increases, however, in the other it decreases because both cases involve increasing the amount of kinetic energy of particles. The only conclusion that can be made from this is that there may be a threshold value at which the speed of particles no long becomes beneficial to the propagation of a sound wave. Such a threshold must exist between each state, solid and liquid, and liquid and solid. At any one of these points, the threshold can be modeled by:

$$F_{\text{velocity of particles}} \leq F_{\text{density of medium}}$$

This expression infers that at the threshold, the influence of density of the medium is greater than the influence of velocity of the particles on the speed at which the sound wave travels.

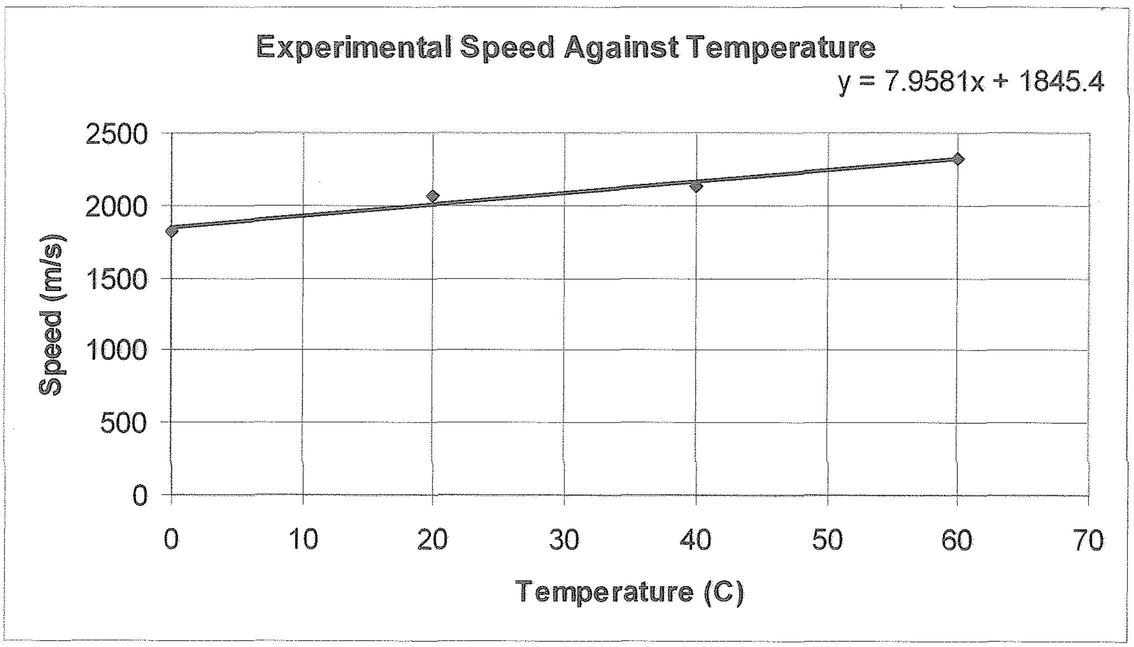
Bibliography

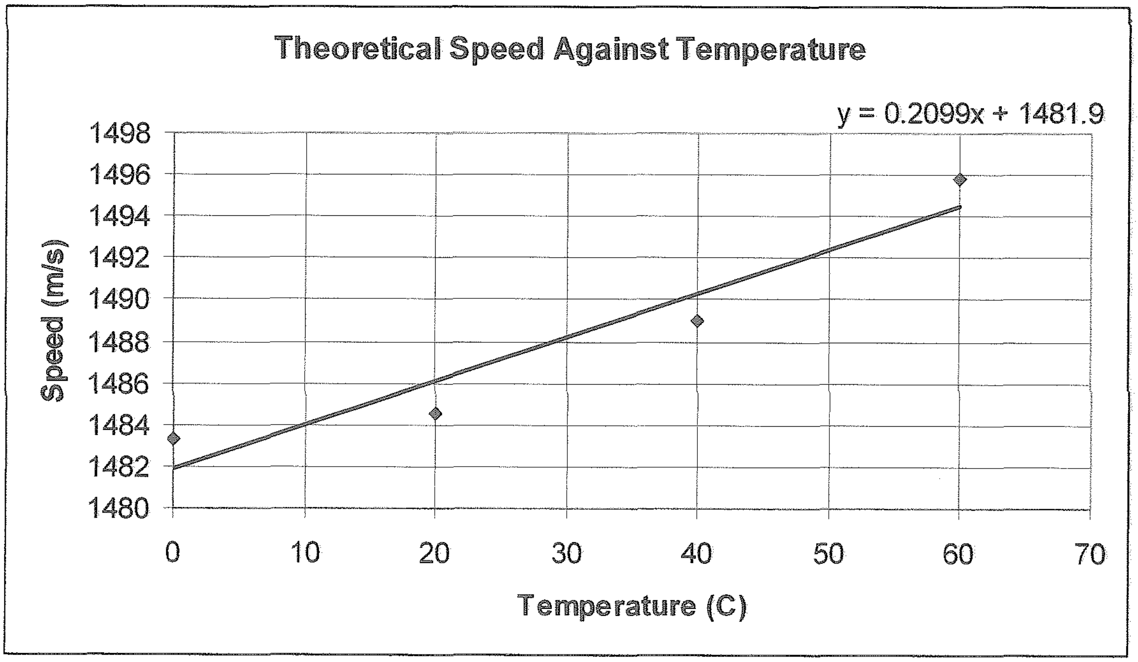
Nave, Carl R. *Hyper Physics*. 2003. Georgia State University http://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe2.html#c3

Senese, Fred. *General Chemistry Online*. 1999. Frostburg State University http://antoine.frostburg.edu/chem/senese/101/measurement/faq/water-density.shtml

Appendix

(Complete)Table 1: Times Gathered from Experiment (ms) ± .05				
	Temperature (°C) ± 5			
Trial	0	20	40	60
1	1.11	0.98	1.03	0.80
2	0.98	0.99	0.84	0.86
3	1.20	0.86	1.10	0.95
4	1.20	0.86	0.99	0.87
5	1.17	0.96	0.95	0.89
6	1.15	0.98	0.86	0.84
7	1.11	1.10	0.93	0.98
8	1.18	0.96	0.97	0.87
9	1.04	0.96	0.96	0.88
10	1.01	1.04	0.91	0.97
11	1.06	0.91	0.95	0.89
12	1.06	0.96	0.93	0.85
13	1.11	0.95	0.96	0.87
14	1.09	1.03	0.94	0.76
15	0.97	0.95	0.90	0.87
16	1.18	0.87	0.83	0.91
17	1.16	1.02	0.86	0.87
18	1.11	1.01	1.01	0.87
19	1.09	1.00	0.96	0.84
20	0.91	0.94	0.93	0.83
21	1.08	1.01	0.84	0.83
22	1.20	0.93	0.87	0.85
23	1.15	1.03	1.00	0.76
24	1.04	1.00	0.95	0.81
25	1.11	0.97	1.02	0.76
Average	1.10	0.97	0.94	0.86


Experimental Speed Against Temperature
y = 7.9581x + 1845.4
Speed (m/s)
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
Temperature (C)


Theoretical Speed Against Temperature
y = 0.2099x + 1481.9
Speed (m/s)
1498
1496
1494
1492
1490
1488
1486
1484
1482
1480
0
10
20
30
40
50
60
70
Temperature (C)